

Lidar Profiling of Sound Speed & Temperature in the Ocean Upper Mixed Layer

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LONG-TERM GOALS

My long-term goals are the exploitation of physics for the solution of significant problems in oceanography. My interests generally lie in the direction of optics and laser interactions/applications in the ocean.

OBJECTIVES

An important Navy and oceanographic requirement is the rapid and accurate determination of sound speed (and hence temperature) profiles in the ocean. Our objective is development and implementation of a new approach to the remote sensing acquisition of upper-ocean vertical sound speed profiles. To this end we are developing an innovative Brillouin LIDAR concept that will provide measurements of temperature and sound speed to an accuracy of 0.1°C and 0.25 m/s, respectively over a range of ≈ 100 m with a range resolution of ≈ 1 m. Our latest results clearly demonstrate the feasibility of this exciting new approach.

APPROACH

Figure 1 shows a conceptual implementation of the Brillouin lidar using a helicopter. The approach is based on the fact that when a laser beam propagates through water, it undergoes Brillouin scattering that consists of two frequency shifted Lorentzian lines centered symmetrically with respect to the frequency of the transmitted laser line. In pure water, the scattering spectrum consists of essentially only this doublet. In the presence of suspended particulate matter (hydrosols), an elastically scattered central line appears. The so-called Brillouin shift, that is to say the frequency shift between the central line (the laser frequency) and each of the Brillouin lines, is typically 7 to 8 GHz for water. The shift is proportional the sound speed in the water and to the refractive index; hence, it also has dependence on the salinity and temperature.

Our detection apparatus (Fig. 2) to measure sound speed (temperature) is based on the Brillouin shift in a LIDAR return. First, the LIDAR return is collimated to an approximately 1.0 cm diameter beam and is then passed through an absorption cell containing $^{127}\text{I}_2$. The laser frequency is tuned so that its second harmonic at 532 nm lies on a strong absorption line of $^{127}\text{I}_2$; consequently, this first absorption cell absorbs all of the elastically scattered light. The transmitted light is divided by a beamsplitter into two equal parts, one of which is detected and provides the normalization signal S_1 . The second half passes through an absorption cell containing $^{129}\text{I}_2$ and is detected to give the signal S_2 . The edges of molecular absorption lines of $^{129}\text{I}_2$ provide the high spectral resolution that is needed for an accurate determination of the Brillouin frequency shifts. Specifically, as the Brillouin shift increases (decreases) the transmission of the $^{129}\text{I}_2$ cell decreases (increases). Simple normalization provides a signal S that depends only on the Brillouin shift and is independent of variations in the amplitude of the LIDAR return; for example, the Brillouin shift is proportional to

either $S_2/(S_1 - S_2)$ or S_2/S_1 . Determination of the proportionality constant is straightforward via measurements of a water sample with known temperature. The concept is extraordinarily simple and robust.

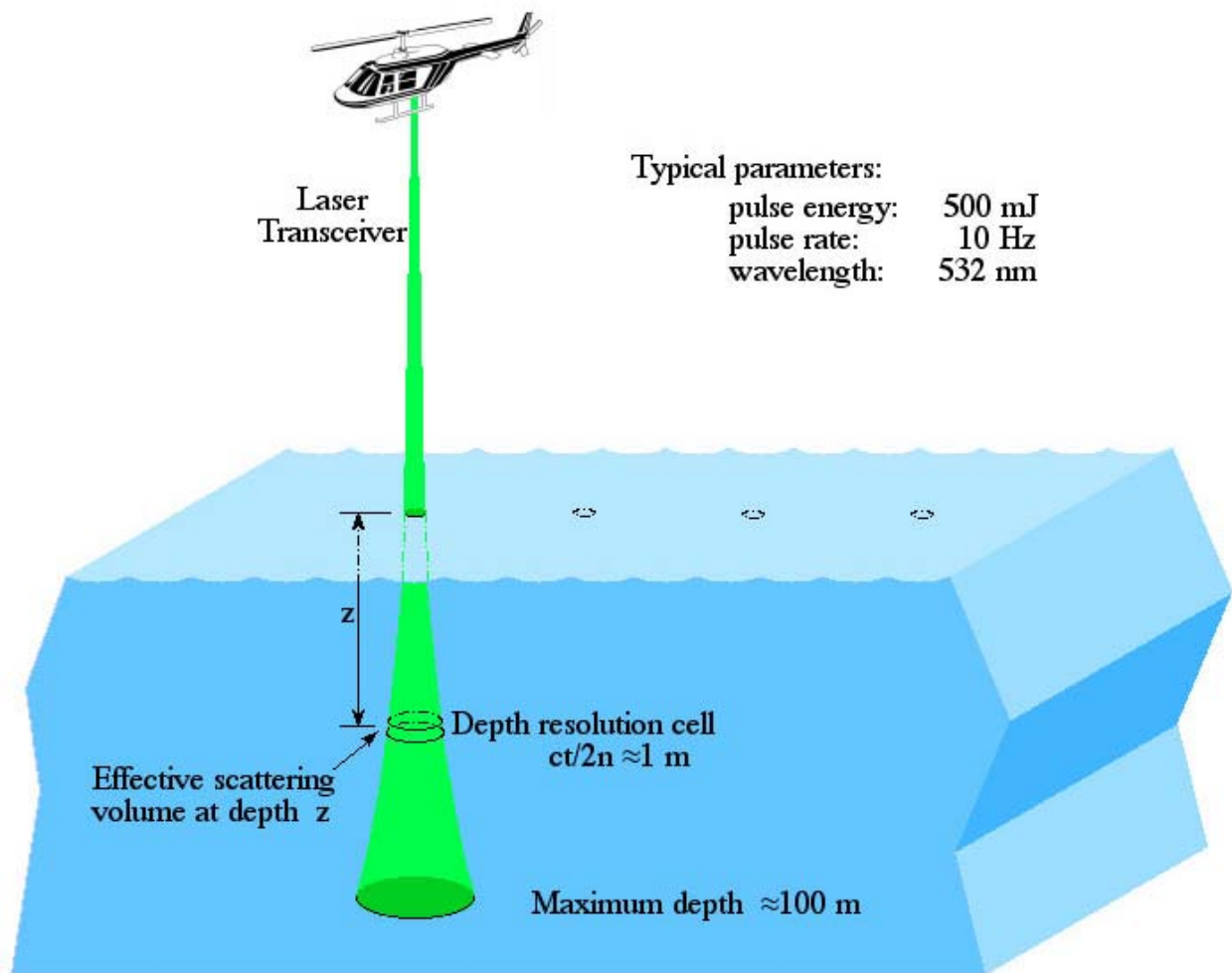


Figure 1. Conceptual implementation in which a laser mounted in a helicopter fires pulses into the ocean. The frequency of the backscattered light is Brillouin shifted. Measuring this shift gives sound speed to an accuracy of ≈ 25 cm/s with a depth resolution of ≈ 1 m.

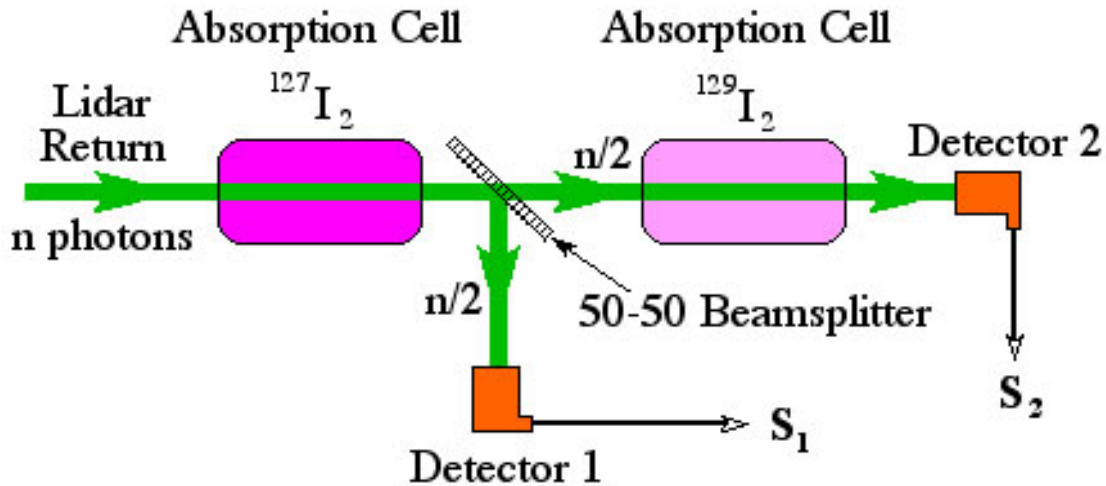


Figure 2. The lidar return first passes through a $^{127}\text{I}_2$ cell that absorbs elastically scattered light. The transmitted light consists of the two Brillouin shifted lines; half is detected to give signal S_1 . The other half passes through the $^{129}\text{I}_2$ cell (edge filter); the transmitted part gives signal S_2 . The ratio $S=S_2/S_1$ uniquely determines the Brillouin shift.

Two individuals in addition to the PI, have participated in the work this year, and one of these for only two months. (1) Dr. Gangyao Xiao: He received his Ph.D. from the Institute of Optics and Fine Mechanics in Shanghai, China. Prior to joining our group in August of 1998, he was an Associate Professor at the National Laboratory on High Power Lasers & Physics in China. Dr. Xiao left our laboratory to take a permanent job with Flextronics International in March, 2001. (2) Mr. Jeffrey Katz: He is a graduate student working full time on the project; this work is the basis of his Ph.D. dissertation.

WORK COMPLETED

Since the successful demonstration of our Brillouin lidar concept last year, we have been working on improving signal-to-noise and minimizing systematics. In particular, considerable effort has gone into stabilization of the laser frequency. Our goal was to do a field test this year, but have not yet done so because we have been concerned that the instrumentation was not yet operating at a level suitable for such a test. Specific items are as follows:

- (1) The CrystaLaser seed laser for our Nd:YAG laser was giving some erratic frequency shifts apparently due to optical feedback from the Nd:YAG laser. So we switched back to using the α -DFB laser as a seed laser. This laser works fine for about a day and then goes unstable and must be retuned to a different set of temperature/current operating parameters; but we decided that at least on a temporary basis, it would meet our needs.
- (2) Unfortunately, it died after just a few weeks and the manufacturer, SDL, Inc., refused to try to fix it. Since they had also discontinued the product, no replacement was available. Thus, we reinstalled the CrystaLaser and purchased another Faraday isolator to protect it against optical feedback from the Nd:YAG laser. Over the last 3 months this has appeared to work extremely well.

- (3) An intensity regulator was installed to stabilize the intensity of the frequency doubled beam used to lock the seed laser to a $^{127}\text{I}_2$ line.
- (4) We have implemented an AO modulator to shift the frequency of the laser beam used for locking the seed laser frequency. The purpose is to more accurately center the Brillouin shifted lidar return on the sides of the $^{129}\text{I}_2$ lines used for the Brillouin frequency shift analysis.
- (5) The electronic circuitry that locks the frequency of the CrystaLaser to an iodine reference line does not work satisfactorily with the feedback reference control provided by the CrystaLaser manufacturer. Work is being done to improve this; in particular we are modifying the manufacturer's electronics in order to access a more suitable control point.

RESULTS

In Fig. 3 we show data from tests implementing the concept shown schematically in Fig. 2 for the Brillouin shift frequency discrimination. This data is different from that shown in last year's report because it corresponds to a different positioning of the laser frequency; in particular, the frequencies of the lidar return are on the opposite side of the set of $^{129}\text{I}_2$ absorption lines used for this data. As before, for this data we used a sample of pure water (0 ‰ salinity) that was ≈ 50 cm deep; so there was no depth discrimination, we just looked at the frequency shift of the total back-scattered signal. Specifically, we measured the signal $S = S_2 / S_1$ as a function of the temperature of the water sample. Since temperature, sound speed and Brillouin shift are uniquely related in pure water [1,2], the plot in Fig. 2 shows the signal S as a function of the measured temperature of the water with an additional axis at the top showing the corresponding Brillouin shift and derived sound speed. The data point at each temperature (sound speed) corresponds to a single laser shot. The results in Fig. 3 were a major milestone. They clearly show that the concept proposed for extracting Brillouin shifts works extremely well!

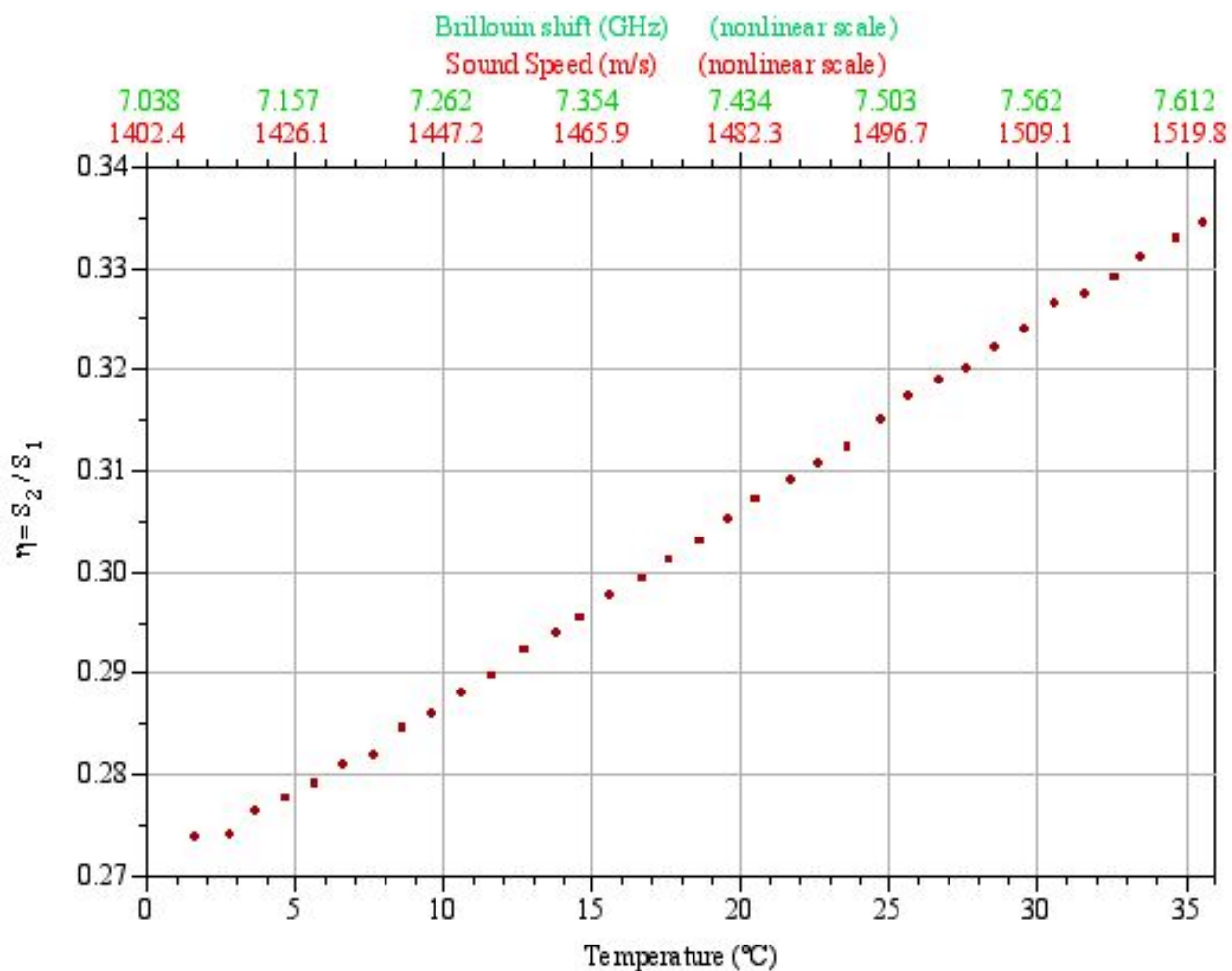


Figure 3. Observed signal as a function of temperature for pure water. The auxiliary axis at the top shows the corresponding Brillouin shift and sound speed (non-linear scale).

IMPACT/APPLICATIONS

The technology we are developing to remotely sense profiles of temperature and sound velocity in the ocean will provide the capability of rapidly monitoring the upper-ocean vertical structure for much of the world's oceans and for most seasons. Such profiles will provide new perspectives on upper-ocean mixing and the oceanic internal wave field. Because of the high heat capacity and circulation in the oceans, temperature profiles are of critical importance to weather forecasting and to the understanding of ocean/atmosphere coupling and global change. Finally, sound velocity profiles are of direct strategic importance to the military mission since they provide support for both active and passive sonar functions; they would also provide an extensive new subsurface data source for operational nowcast/forecast systems.

TRANSITIONS

We signed an agreement with Continuum, Inc. to modify one of their lasers to run single frequency in the same way that we have modified the laser we purchased from them for this project. They have been impressed by what we had accomplished with it and are planning to implement it as a product.

Our efforts have attracted considerable interest elsewhere. In particular, Dr. Dahe Liu, who is a professor from Beijing University and who was a visiting scholar in my laboratory in 1997 and 1998, is attempting a similar development in China. He is the one that helped us acquire the iodine isotope ^{129}I from China; it is required for the frequency analysis of the LIDAR return.

Another researcher in China, Dr. Zhishen Liu, is at the Ocean University of Qingdao. He has been closely following this work in the literature and has visited our laboratory. He recently sent one of his colleagues, Dr. Wu Dong, to work with us for a short period of time.

RELATED PROJECTS

This project was co-funded with a grant from the Texas Advanced Technology Program entitled “Brillouin LIDAR for Ocean Temperature/Sound Velocity Profiling, Mine Detection, and Bathymetry”; the grant expired in August, 2000.

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